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FACE PUMPED LASER

Final Technical Report

1 June 1966 - 30 November 1966

ONR Contract No. Nonr-4659(00)
Project Code No. 4730
ARPA Order No. 306

Prepared for

Office of Naval Research
Department of Navy
Washington 25, D. C.

Prepared by

RESEARCH AND DEVELOPMENT CENTER
General Electric Company
Schenectady, N. Y. 12301

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FACE PUMPED LASER

Final Technical Report

1 June 1966 - 30 November 1966

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Submitted by

Heavy Military Electronics Dept.
General Electric Company
Syracuse, New York

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Section I

INTRODUCTION

The following is the final report on investigations of the face pumped laser technique under ONR Contract No. Nonr-4659(00) and ARPA Order No. 306. The next section describes the work performed during the last six months of the program while Section III reviews the overall program objectives and summarizes the results obtained.

Section II

WORK PERFORMED FOR PERIOD 1 JUNE 1966 - 30 NOVEMBER 1966

A. AMPLIFIER GAIN CHARACTERISTICS

The small signal gain characteristics of a five disc amplifier chain described previously* were first determined by measuring the ratio of the output to input signal as a function of flash lamp electrical input pump energy. A beam splitter provided a sample of the input signal energy which was directed through appropriate filtering to a photodiode. A small signal S_i proportional to the input energy was displayed on an oscilloscope employing an operational amplifier as a pulse integrator. A similar technique provided the amplified output signal $S_o(P)$ which was a function of the pump energy P. The small signal gain as a function of P is given by

$$G(P) = \frac{S_o(P)}{S_i(P)} \cdot \frac{S_i(0)}{S_o(0)}$$

where the second ratio on the right hand side of the equation is formed from the values of S_i and S_o when the laser discs are unpumped (P = 0). Sufficient data from previous experiments were available to allow a calculation of the gain expected for a given flash lamp input pump energy (P). The measured gain was only 65% of that calculated.

In order to help resolve this discrepancy the gain was also measured by using the disc in an oscillator configuration where the lasing threshold is measured for several values of output mirror reflectivity. As pointed out in a previous description of the technique, this procedure sets a lower limit on the gain**. The gain calculated from the oscillator experiment data was 85% of that

* "Face Pumped Laser," General Electric Company, Third Semi-Annual Technical Report, ONR Contract No. Nonr-4659(00), 1 December 1965 - 31 May 1966, p. II-23

** "Face Pumped Laser," General Electric Company, Second Semi-Annual Technical Report, ONR Contract No. Nonr-4659(00), 1 June 1965 - 30 November 1965, p. II-45

predicted for the flash lamp input energy used but this agreement was deemed satisfactory since the former value is a lower limit and the latter value is based on a theoretical calculation involving parameters whose values are somewhat uncertain.

The low value of amplifier gain calculated from the ratio of output to input is attributed in part at least to a mismatch between the wavelength of input signal and the peak in the amplifier gain spectrum. The input signal was found to consist of approximately eight longitudinal modes spanning a wavelength interval of ~26 Å and centered at ~10,585 Å. This beam originated from a rod oscillator employing Eastman Kodak ND-11 Silicate laser glass with 2% Nd doping; the disc amplifier used AOLux 3835 barium crown glass containing 5% Nd doping with a fluorescent line which is said by the manufacturer to be centered at 1.06 μ wavelength. While the exact gain spectrum for the laser disc is not known with sufficient accuracy to allow an assignment of complete responsibility for the discrepancy in gain measurements to wavelength mismatch, the latter appears to be the only explanation compatible with all the data.

Ideally, we would like to plot the small signal gain against the inversion energy density (joules/cm^2). If our experiments have been accurate, such a plot would produce a straight line, whose slope could be compared with the published gain per unit of inversion density. However, the inversion energy density is not directly measurable so we have settled for an easily, directly measured quantity, the pump energy density transmitted through the laser disc, which is essentially proportional to the inversion energy density. The proportionality factor is not quite independent of the level of pumping energy due to the spectral shift of the flash lamps. However, the effect of spectral shift is minimized because the pump light incident upon the laser disc is filtered to remove the u.v. and i.r. components. Figure A1 shows the small signal gain for one round trip reflection from a single disc module of the amplifier (as determined from

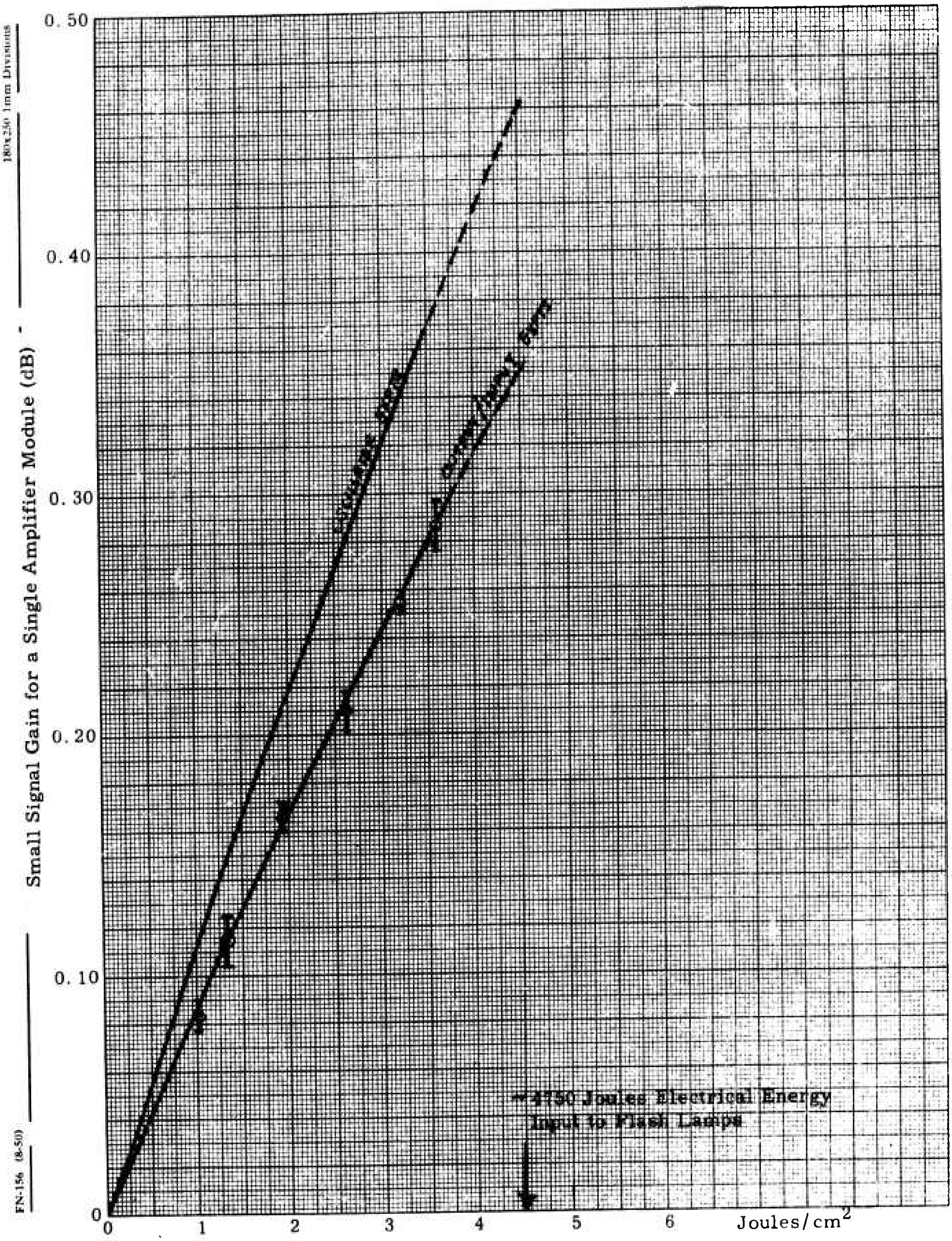

Fig. A1. Small Signal Gain for a Single Amplifier Module versus Pumping Energy Density Transmitted Through Laser Disc

the ratio of output to input signal) versus the pump energy density transmitted through the laser disc. The slight curvature of this gain line is explained by the spectral shift. Also shown is a second gain line which is 1.31 times the first and represents the gain in the absence of wavelength mismatch given by the oscillator experiments. The fact that the gain curve does not exhibit a rather sharp break in its slope is evidence that amplified spontaneous emission is not important for the range of pumping levels in this experiment. Such a sharp break actually was observed before the side of each laser disc was painted black.

The maximum gain is governed by the amplifier design and flash lamp explosion limit. For the present design operated at the highest level recommended for the flash lamps (4750 joules electrical energy input) the maximum gain for one reflection off the separate mirror (two passes through the laser disc) is slightly less than $\frac{1}{2}$ dB ($\frac{3}{4}$ joules/cm^2 of stored inversion energy). However, an extensive and detailed review of the data obtained from all previous experiments on face pumping now indicates that with an improved design, this gain figure may be increased substantially.

Details of the gain optimization are given in Section F but a brief summary of the sources of this increased inversion is given below.

1. Optimize the shape and duration of the pump pulse.
2. Reduce spontaneous emission losses by using a longer lifetime (900 μsec) laser glass.
3. Improve optical coupling between lamps and disc by liquid immersion of intermediate surfaces for the reduction of interface reflection losses.
4. Increase optical coupling by improving the geometry of the reflector behind the pump lamps.
5. Increase absorption of available pumping radiation in the laser glass with an optimized choice of thickness and Nd concentration.

The analysis in Section F is for an active mirror configuration in contrast to the separate mirror configuration used in the experiments described in this section. It should be noted that the active mirror will of course warp under pumping with the primary effect being a time dependent weak spherical distortion of the reflected wave front. At the end of the approximately square pumping pulse, the spherical distortion will reach its maximum and afterwards change slowly since the thermal relaxation time of the glass is many seconds. If an input signal is amplified immediately after the pump pulse, the spherical distortion will be essentially static during the signal because of the relatively long thermal relaxation time of the disc. This will be especially true if the duration of the input signal is very short such as from a Q-switched laser. This type of distortion can be corrected with a weak spherical lens. In practice it is expected that a single lens will be used to both focus and correct the output beam from a chain of active mirror amplifiers. It is concluded that the active mirror configuration will be very satisfactory in terms of its distortion characteristics in many applications.

On the basis of the analysis in Section F, it appears possible to achieve an inversion of ~ 3.2 joules/cm^2 with an efficiency (total stored inversion energy divided by electrical input energy) of $\sim 2.1\%$. For the long lifetime glass with a gain coefficient of $\frac{1}{4}$ dB/joule stored/cm^2, the small signal gain would be 1.6 dB per round trip reflection from the active mirror.

If the separate mirror configuration is used with no index matching liquid between the mirror and laser disc, then two additional reflection losses are added. In that case the small signal gain per round trip reflection from a single module is calculated to be ~ 1.3 dB under optimum conditions.

B. AMPLIFIER DISTORTION - THEORY

Distortion by a laser amplifier may be divided into two categories; 1) residual distortion produced by the tolerances of the optical components of the laser amplifier when it is unpumped and 2) additional distortion associated with pumping. When a diffraction limited, collimated beam is brought to a focus by a lens, a certain intensity distribution obtains in the region of the focus. If the wave front of this beam is distorted across its aperture then the intensity in the region of the focus is reduced from what would obtain in the absence of such distortion. The most severe reduction in intensity occurs at the diffraction focus (the point of maximum intensity). However, the power which no longer arrives at the diffraction focus is mostly re-distributed within a distance equal to an Airy disc diameter.

While the detailed intensity distribution of the diffraction pattern is difficult to calculate, a formula has been developed which gives the reduction in intensity at the diffraction focus which results from wave front distortion. Quite generally, for uniform amplitude over the wave front and small aberrations (departure of the wave fronts from a spherical form by only a fraction of a wavelength), the normalized intensity (I) in the region of the focus is independent of the nature of the aberration and is smaller than the ideal value unity by an amount proportional to the mean-square deformation of the wave front*, $(\Delta\Phi)^2$. That is:

$$I \sim 1 - \left(\frac{2\pi}{\lambda}\right)^2 (\Delta\Phi)^2 \tag{1}$$

where

$$(\Delta\Phi)^2 = \frac{\int (\Phi-\bar{\Phi})^2 \, dS}{\int dS}$$

and $\Phi - \bar{\Phi}$ is the fraction of a wavelength that the wave front in question departs from the reference sphere which is centered on the diffraction focus. The details and precise definitions appropriate to the diffraction theory of aberrations are

* Born and Wolf, Principles of Optics, Second Edition, Pergamon Press (1964) Chapter IX

given elsewhere* but the results expressed in the above equations are sufficient to allow an <u>estimate</u> of the loss expected from distortion by our laser amplifier.

First, consider the cold amplifier distortion produced by imperfect optics. Our typical laser disc is flat and uniform in thickness to $\pm\lambda/20$ at the laser wavelength. Part of this departure from flatness is equivalent to a weak spherical lens which simply has the effect of defining a new reference sphere (i.e., changing the position of the diffraction focus). Let us assume then that the maximum non-spherical departure from flatness is $\pm\lambda/40$. When we examine a wave front transmitted through such a disc, the optical path variation differs from the non-uniformity of the geometric thickness by a factor of (n-1) where n is index of refraction of the disc, approximately 1.5. The mean-square deformation is of course smaller than the maximum square deformation and we estimate their ratio to be $\frac{1}{2}$. Therefore a very rough estimate of the mean-square deformation for transmission through a disc is:

$$(\Delta\Phi)^2 = \frac{1}{2} \cdot \left[\left(\frac{\lambda}{40}\right)(n-1)\right]^2 = \frac{1}{2}\left(\frac{\lambda}{80}\right)^2$$

Substituting into Eq. (1) we find that the normalized intensity at the diffraction focus is

$$I = 1 - \left(\frac{2\pi}{\lambda}\right)^2 \frac{1}{2}\left(\frac{\lambda}{80}\right)^2 = 1 - 0.0031$$

i.e., we may expect to lose roughly $\frac{1}{3}\%$ of the intensity at the diffraction focus due to transmission through one of our laser discs.

It might well be asked what the effect is of placing in tandem m discs of similar tolerances (but with randomly oriented aberration). While the root mean-square deformation of the ensemble will only increase as the square root of m, the intensity loss is proportional to the mean-square deformation or the first power of m within the limitation that the total loss remains small.

---

* Born and Wolf, <u>Principles of Optics</u>, Second Edition, Pergamon Press (1964) Chapter IX

The intensity loss suffered upon reflection from a mirror with optical tolerances similar to those of the disc will be $\sim 8/3\%$, an extra factor of 4 occuring because the $(n-1)^2$ factor no longer applies and a factor of 2 being introduced because the phase aberration is doubled upon reflection. Since one reflection off the mirror of a single amplifier module requires two transmissions through the disc, a single round trip through one amplifier module should produce an intensity loss at the diffraction focus of approximately $3\frac{1}{3}\%$. In our amplifier experiments we actually make 8 round trips through single modules, one reflection off a return mirror, and 9 reflections off other mirrors. Therefore we expect a total loss of $\sim 50\%$ while keeping in mind that the formulas involved are inaccurate for such a large loss. This large magnitude of loss may appear ominous, but it should be recalled that while the maximum intensity at the diffraction focus may be reduced by a large amount, the integrated power falling upon an area equivalent to the Airy disc of the undistorted Fraunhofer diffraction pattern will be reduced by considerably less. That is, most of the energy lost from the diffraction focus reappears (is redistributed) within a circle of diameter equal to one or two Airy disc diameters.

The additional distortion occuring during pumping may also be estimated. Non-uniform pumping causes a variation in the optical thickness due to uneven thermal expansion. This effect has been considered* and shown to produce variations in optical thickness approximately one order of magnitude smaller than those variations found in the "cold" disc. Thus the mean-square deformation due to the thermal expansion variations arising from non-uniform pumping will be two orders of magnitude smaller than that arising from $\frac{1}{10}$ wave tolerances on the optical components and therefore negligible. While we have not carried out very detailed calculations on stress birefringence effects and other aberrations associated with pumping, for the optical configuration under consideration here

* "Face Pumped Laser," General Electric Company, Third Semi-Annual Technical Summary Report, ONR Contract No. Nonr-4659(00), 1 December 1965-31 May 1966, p. II-13

these effects appear to be of the same order or smaller than the thermal expansion effect. The thermal warpage of the disc also produces only second order effects when the disc is used in the separate mirror configuration. The experiments for measuring distortion employ the separate mirror configuration and thus pumping is not expected to contribute appreciable distortion to the amplifier system when compared with that expected from the tolerances of the optics.

C. COLD DISC DISTORTION MEASUREMENTS

A simple experiment was conducted in order to determine empirically the contribution to beam distortion caused by the optical tolerances of the cold (unpumped) laser discs. Figure C1 portrays the experimental arrangement. A He-Ne gas laser with a beam expander was used in conjunction with a telescope objective lens and aperture to provide a $2\frac{1}{2}$" diameter collimated uniphase beam of approximately uniform amplitude while a second telescope objective was used to form the Fraunhofer diffraction pattern. A microscope objective was employed to magnify the diffraction pattern and a variable diameter circular aperture was located in the image plane. Behind the aperture was a photodiode which was used in conjunction with the aperture to measure the diffraction pattern intensity distribution. This intensity distribution was determined with and without four laser discs in the collimated gas laser beam. The discs themselves are simply stacked next to each other on a V-block since a pumping means and mirrors are not required for this experiment in contrast to subsequent amplifier distortion experiments. We then calculated the fraction of the total energy in the diffraction pattern (for no distortion) which is accepted by a circular aperture of diameter αd_A where d_A is the theoretical Airy disc diameter (which agrees with the observed value) and α is a proportionality factor. The results are as follows:

Circular Aperture Diameter	Theoretical % of Total Energy (No Distortion)	Experimental % of Total Energy (Four Discs)	Experimental % of Total Energy (Zero Discs)
2 d_A	91.2	90.6 ± 1.1	91.1 ± 2.3
1 d_A	83.8	79.8 ± 1.5	83.2 ± 2.2
0.6 d_A	71.3	68.8 ± 1.8	72.3 ± 1.9

The data in the last column for "zero discs" agrees well with the theoretical predictions for no distortion (second column). With four discs in the beam however, the observed energy in the two smaller diameter circle is roughly 4%

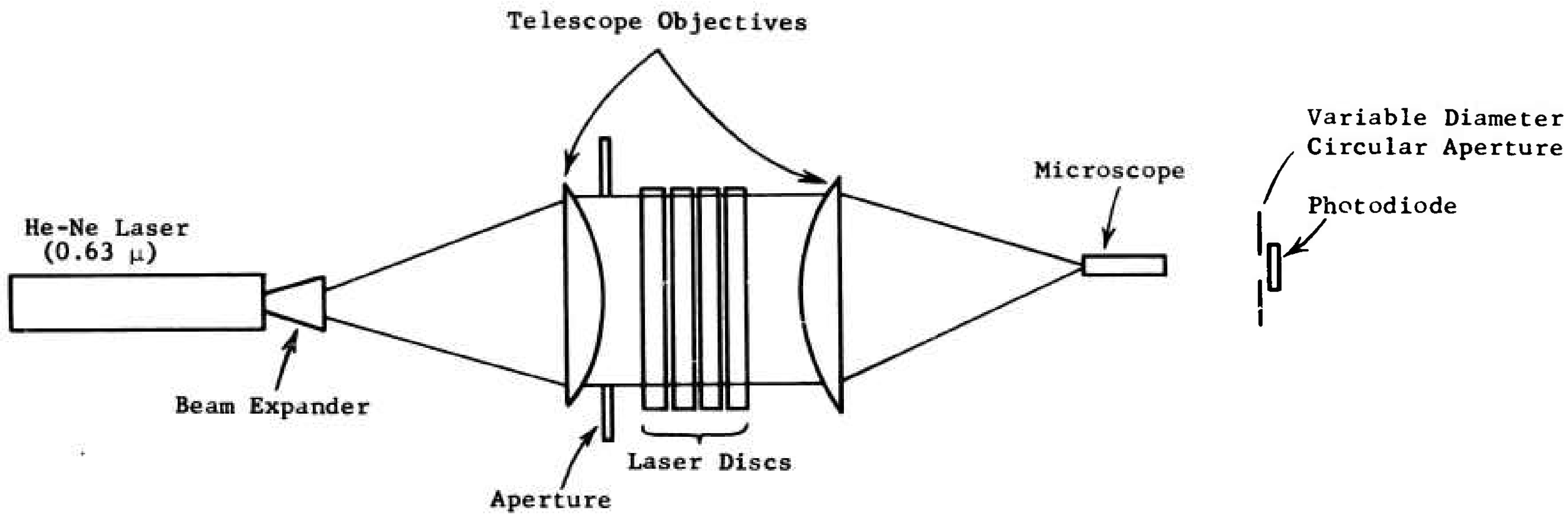

Figure C1. Experimental Arrangement for Measuring Unpumped Disc Distortion Effect

below that which would obtain in the absence of distortion. This is more than the 4 x $\frac{1}{3}$% = $1\frac{1}{3}$% effect which we would predict (see earlier section), probably due to a small lateral displacement of the diffraction pattern by the wedge angle of the discs. No correction for such an effect was made. This simple experiment while inconclusive for the smaller diameter aperture, does show that the optical tolerances of four laser discs in series do not measurably (within experimental error of $\sim$1.2%) reduce the energy within an area of diameter 2 d_A in agreement with expectations (see earlier discussion of distortion theory).

D. QUALITATIVE DISTORTION ANALYSIS

Next, a set of experiments was conducted to record the Fraunhofer diffraction pattern photographically under a variety of conditions. The resultant pictures provide a qualitative measure of distortion effects. Subsequent experiments described in the following section yielded quantitative data on distortion effects.

Figure D1 shows the schematic arrangement for photographically recording the diffraction patterns. This system is essentially the same as that described earlier* except that a plane mirror Q behind the microscope diverts the beam into a lensless camera. Also the beam splitter F is not employed when the camera is in use and only four amplifier modules were used. Figures D2-D5 are photographs of the experimental arrangement.

In order to assure single mode operation of the driver oscillator, one circular aperture was placed in front of the sapphire etalon output reflector, and a second aperture in front of the spherical mirror of the hemiconfocal optical cavity. In this configuration, the spot diameters calculated from theory are 0.070" at the etalon, and 0.099" at the spherical mirror. For a Gaussian beam, 86.5% of the beam energy is contained within the spot diameter and 99.97% within twice that diameter. We operated the pair of apertures so that in one case they were opened to the dimensions of the respective spot diameters, and in a second case at twice these diameters. In both cases single transverse mode (TEM_{00}) output was achieved as determined from an examination of the Fraunhofer diffraction patterns. However the larger set of diameters was used for the amplifier distortion measurements since the output power of the driver was substantially larger with that arrangement as might be expected.

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* "Face Pumped Laser," General Electric Company, Third Semi-Annual Technical Summary Report, ONR Contract No. Nonr-4659(00), 1 December 1965-31 May 1966, pp. II-23-25

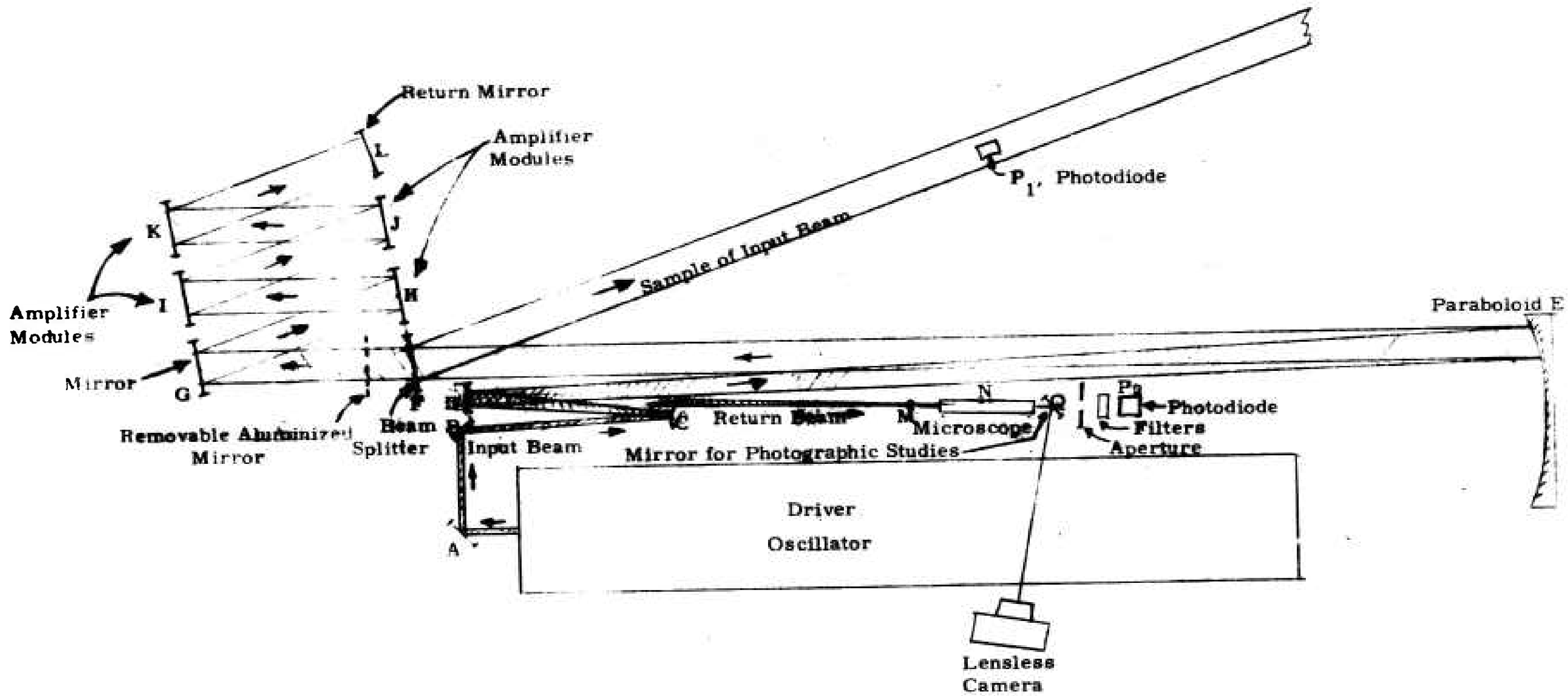


Fig. D1 Schematic Arrangement of Four Disc Amplifier Distortion Experiment

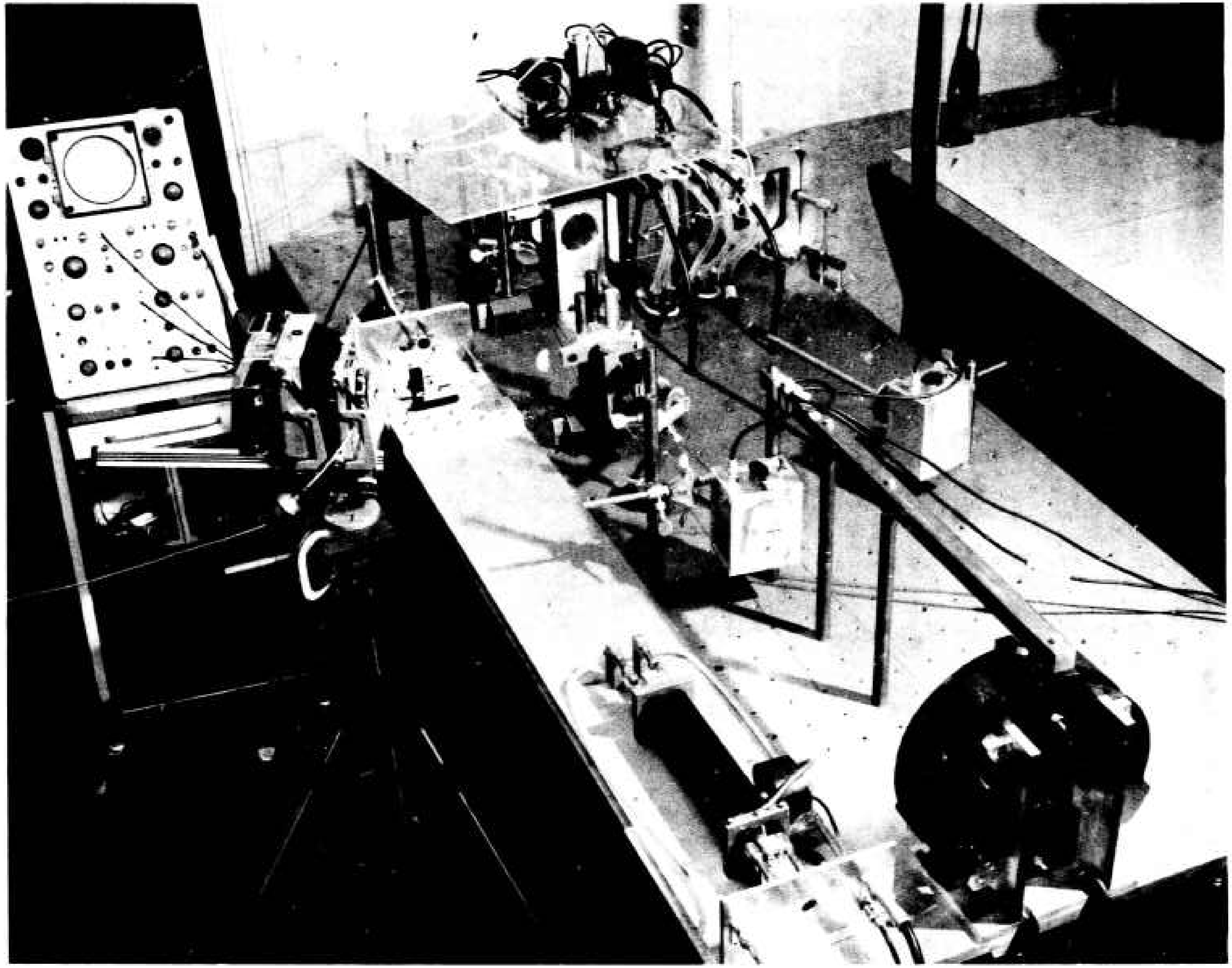


Figure D2. Photograph of Amplifier Distortion Experiment: Cover Removed from Driver Oscillator (Center Foreground).

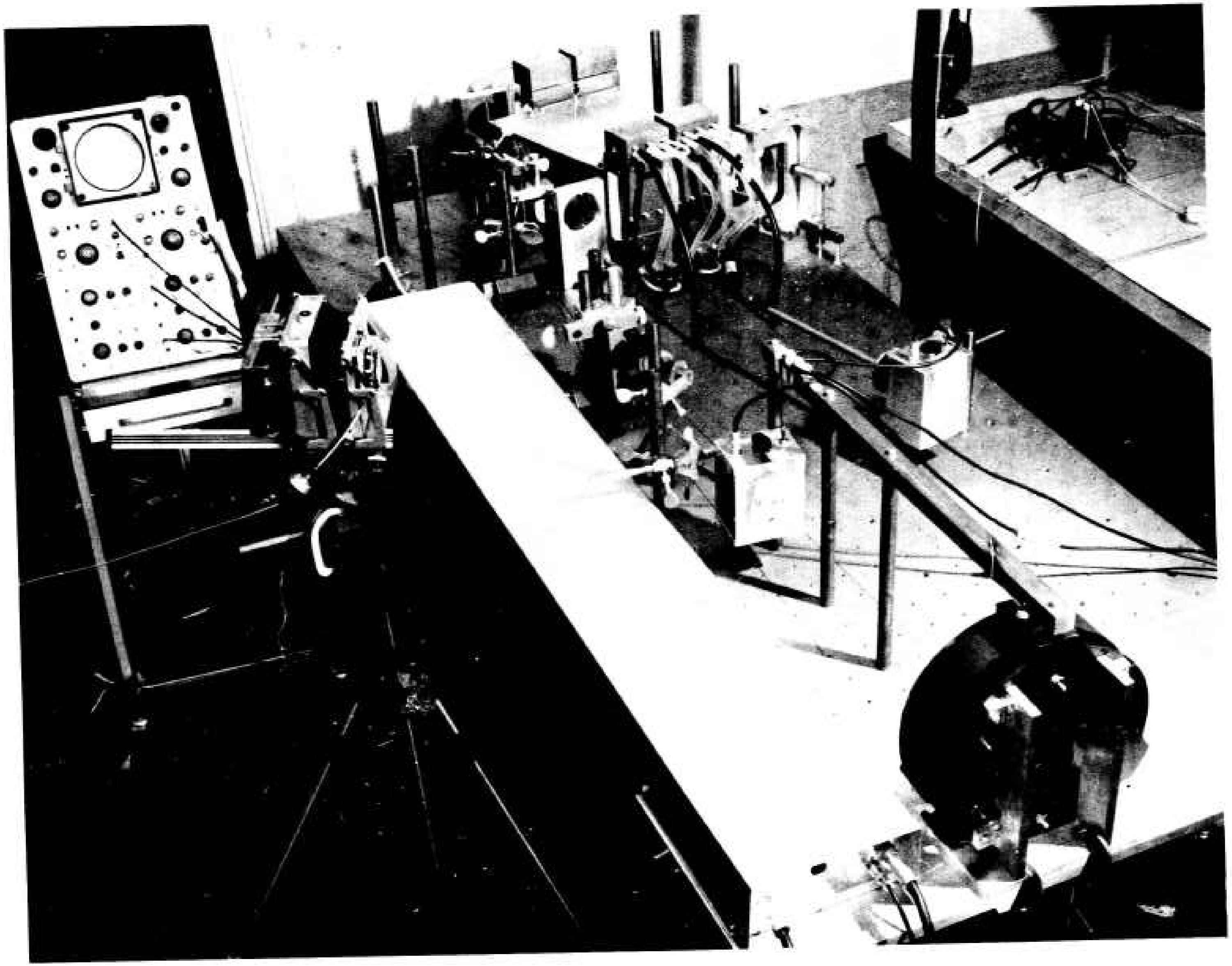


Figure D3. Photograph of Amplifier Distortion Experiment: Amplifier Trigger Transformer Deck Removed (Center Rear).

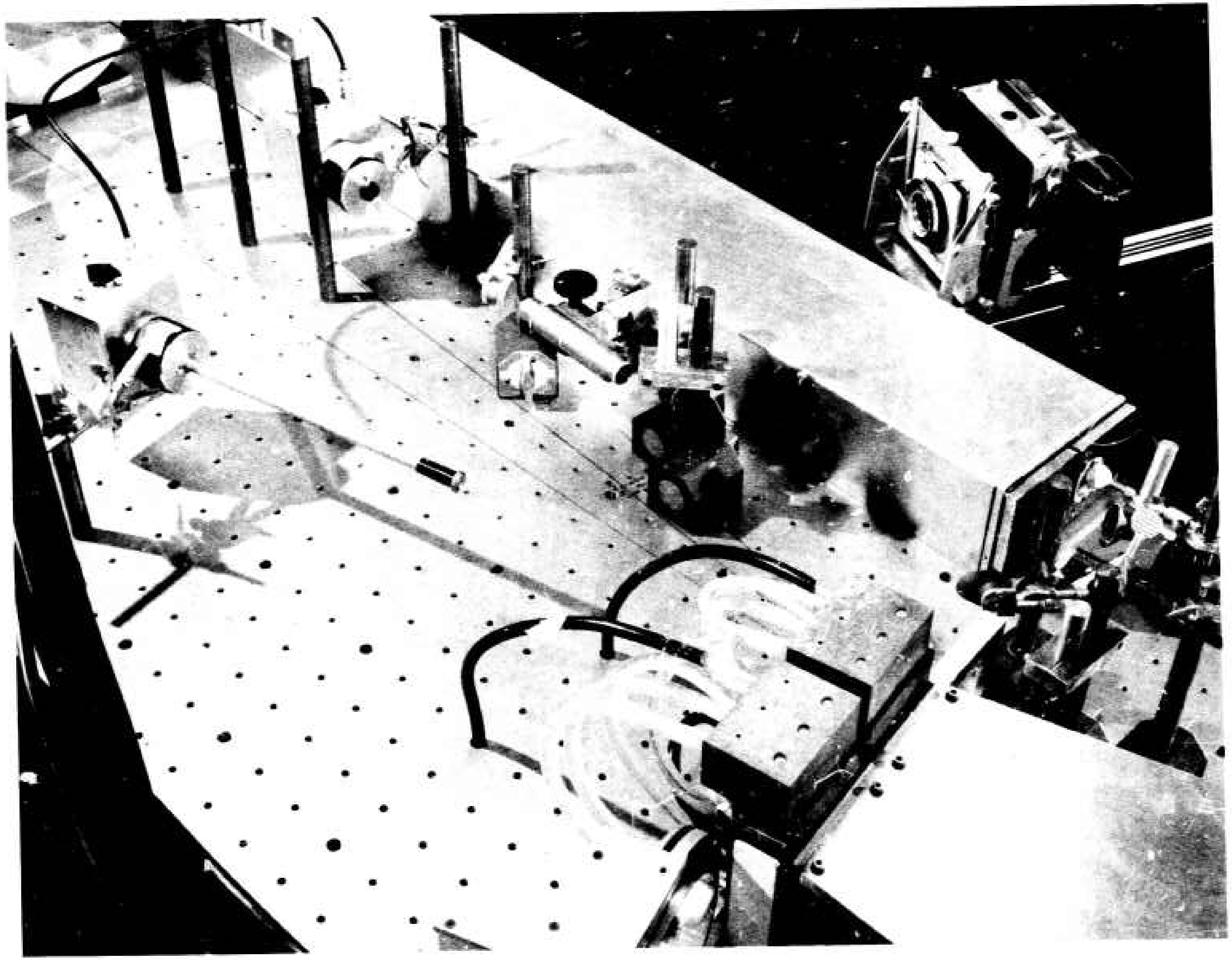


Figure D4. Photograph of Measuring Optics of Amplifier Distortion Experiment.

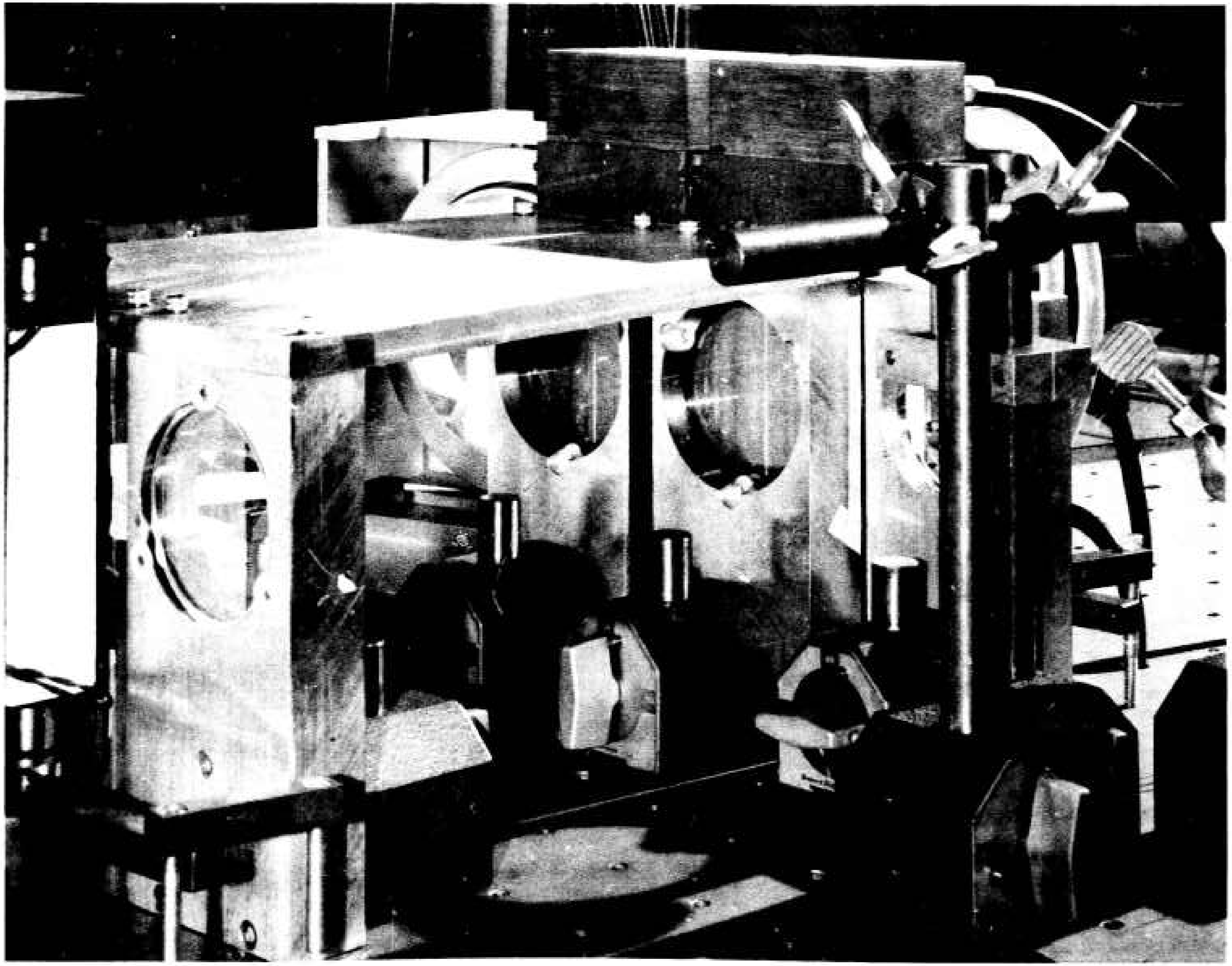


Figure D5. Photograph of Four Disc Amplifier.

To calibrate and check this system, the following auxiliary experiment was conducted. The output beam of a He-Ne gas laser (λ = 0.6328 microns) was passed through the two apertures within the driver oscillator and then followed the same optical path as would the driver output beam. In order to calibrate and check the fore-optics of the experiment, an aluminized mirror was introduced at the entrance of the amplifier and served to short circuit the amplifier and fold the gas laser beam back on itself so the beam returns to the microscope without passing through the amplifier chain. In order to produce a larger diffraction pattern without changing the basic optics, a 1.5" diameter aperture was placed in the beam, assuring uniform aperture illumination while doubling the Airy disc diameter. Because this aperture was placed in front of the paraboloid where the input and return beams are slightly separated, the limiting aperture is effectively elliptical which results in a correspondingly elliptical diffraction pattern as shown in Figure D6a. This pattern has the theoretically expected dimensions and serves as a check on the optical quality and magnification characteristics of the measuring optics.

Next the $1\frac{1}{2}$" diameter aperture is removed, while the aluminized mirror in front of the amplifier is retained, the driver oscillator is made to lase and the Fraunhofer diffraction pattern is recorded. A typical result is shown in Figure D6b. The absence of a noticeable ring pattern is explained by the fact that the ring structure is theoretically predicted to be weaker due to an appreciable amplitude taper over the 3" limiting aperture formed by the aluminized mirror (or the amplifier in later experiments). In fact the amplitude of the Gaussian output beam has fallen to ~1/e at the point where it intercepts the three inch diameter aperture. The Fraunhofer diffraction pattern corresponding to just this arrangement has been calculated*. The diameter of the overexposed

* Spectra-Physics Laser Technical Bulletin Number 5, Spectra-Physics Inc., Publisher

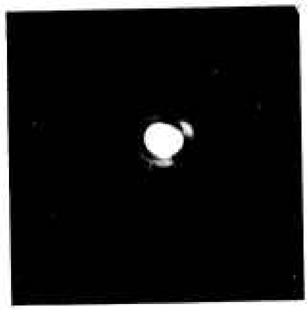


Figure D6a. Photograph of Fraunhofer Diffraction Pattern for 1.5" Diameter Aperture, 0.6328 Micron Wavelength, and Measuring Optics Only.

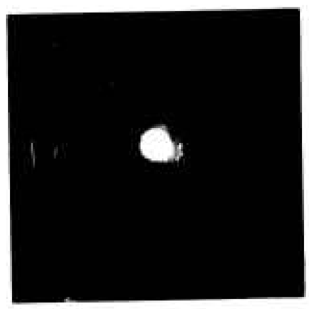


Figure D6b. Photograph of Fraunhofer Diffraction Pattern for 3" Diameter Aperture, 1.06 Micron Wavelength, and Measuring Optics Only.

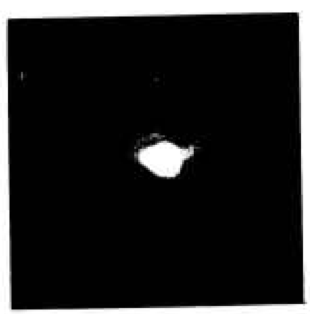


Figure D6c. Photograph of Fraunhofer Diffraction Pattern for 3" Diameter Aperture, 1.06 Micron Wavelength, Measuring Optics and Unpumped Amplifiers.

(white) center agrees closely (~7% discrepancy) with the first theoretically predicted minimum, which defines a circle containing $\sim 92\frac{1}{2}\%$ of the total diffracted energy.

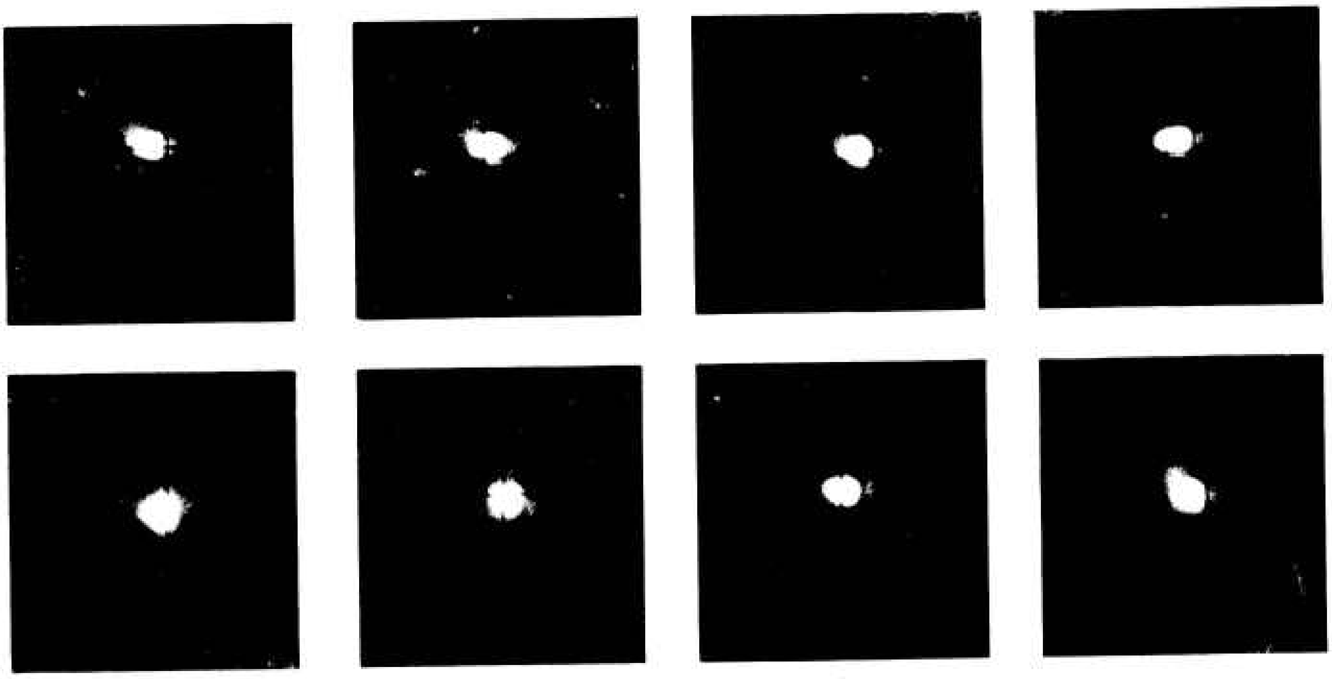
Now the aluminized mirror in front of the amplifier is removed so that the output of the driver oscillator will pass through the amplifier, reflect off the return mirror back through the amplifier having thus struck 8 single disc modules. See Figure D1. When this is done with the discs unpumped ("cold" amplifier) a diffraction spot such as that shown in Figure D6c results. This picture shows some ellipticity and a small extra lobe on the left. Approximately 10 to 15% ellipticity is predicted because the input and output beams are slightly separated and also incident upon the amplifier optics at approximately 10 degrees off normal. This means that the effective aperture formed by the amplifier optics is shorter than 3" along the horizontal axis causing an elongation in the diffraction pattern in this direction. The origin of the apparent extra lobe is uncertain but it is presumably a cold amplifier distortion effect. However, even with this lobe included, the width of the overexposed region appears to have increased beyond that expected for a distortionless amplifier by only a small amount (~20%). It is of course difficult (and often misleading) to estimate changes in intensity distributions by simple visual comparison of photographs. However these photographs do provide some information, especially when coupled with the photodiode measurements described later.

One particular utility of these photographic studies is that they present a simple means of following any displacement of the diffraction spot, especially that associated with pumping-induced vibration of the various optical components (particularly the mirrors) of the system. Although an attempt was made to mechanically strengthen the amplifier structure in order to reduce the amplitude of the pumping-induced vibration* this unsophisticated effort was only moderately

* For a discussion of this effect see "Face Pumped Laser," General Electric Company, Third Semi-Annual Technical Summary Report, ONR Contract No. Nonr-4659(00), 1 December 1965-31 May 1966, pp. II.21-25

successful. Since the amplifier structure was not sufficiently stable, it was necessary to take a new photograph of the diffraction spot just prior to triggering the amplifier pump lamps for each time they were triggered. Figure D7a-d shows several pairs of pictures taken at different time intervals following the amplifier pump lamps. On the top row are shown the diffraction spots photographed prior to triggering. On the bottom row are shown the photographs taken at the noted delay time after the amplifier trigger pulse. The "exposure" time of these pictures is of the order of 80 microseconds, determined by the output duration of the driver oscillator. Actually the driver output consists of several spikes as shown in Figure D8a. Figure D8b shows that the individual spikes are ~1 microsecond wide at half power. The picture taken at ~630-720 μsec after the amplifier is triggered (Figure D7a) spans the time of maximum inversion in the amplifier which is the time when a signal of small time duration compared with the millisecond pumping pulse would generally be sent through the amplifier in order to receive maximum gain. In this picture (which is typical of many taken at this time delay) the diffraction spot has moved vertically ~1.6 beam diameters and horizontally ~0.2 beam diameters where the beam diameter is taken to be the diameter of the overexposed (solid white) spot in the photograph in Figure D6b. Actually a deflection of the beam by 0.2 beam diameters is within the "noise level" of the experiment since displacements of this order were found to occur even when the amplifier is not pumped. It should be noted that one beam diameter corresponds to $\sim 3.2 \times 10^{-5}$ radians. In order to displace the diffraction pattern by 0.2 beam diameters, a shift at one edge of a 3" diameter amplifier mirror of only 1/10 micron is required. Hence the observed "noise" is not unexpected. The horizontal beam width in Figure D7a (630-720 μsec AFTER) is approximately unchanged although the vertical width is increased somewhat. This increase is caused by the 80 μsec long exposure during which the diffraction spot is moving vertically. The vertical motion results in a displacement of only a fraction of

Before Before Before Before



630-720μsec After | 0.5 Sec. After | 1 Sec. After | 2.5 Sec. After

(a) (b) (c) (d)

Figure D7. Photographic Study of Diffraction Spot Displacement Versus Time after Amplifier Pumping Is Initiated.

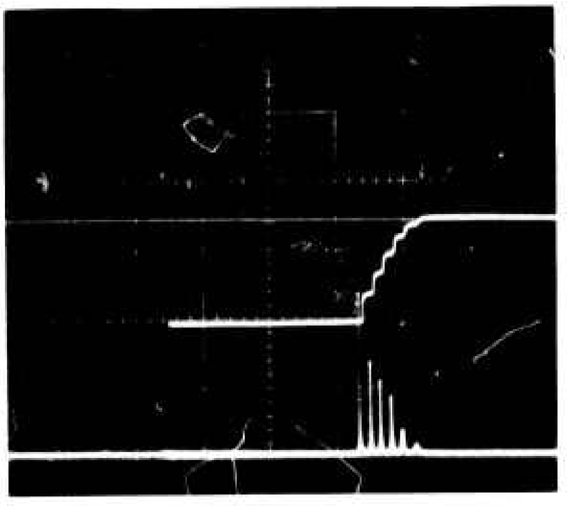


Figure D8a. Driver Oscillator Output (100μsec/div.): Upper Trace Is Cumulative Energy; Lower Trace Is Intensity.

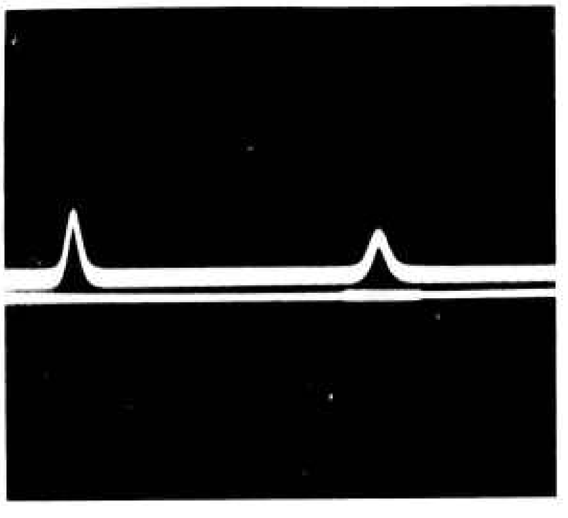
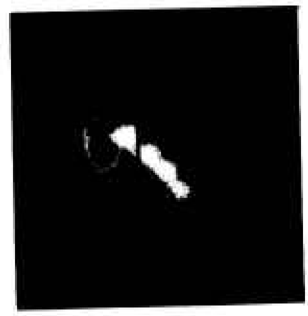


Figure D8b. Two Driver Oscillator Output Spikes (5μsec/div.).

a beam diameter during the exposure time so the apparent increase in the vertical beam width is rather small. However, 1050 μsec after the amplifier is triggered (~350 μsec after maximum inversion) the vibration induced by the pumping has resulted in a more rapid displacement of the diffraction spot and the exposure time results in a streak photo as shown in Figure D9a. At 1300 μsec after the amplifier is triggered, the motion is sufficiently rapid that the diffraction spot translates approximately one diameter during the time between the driver oscillator spikes. The photograph in Figure D9b shows "time resolved" position of the diffraction spot with apparently only four spikes having sufficient energy to expose the film. The pictures taken with delay times of the order of one second (Figure D7b, c, d) show that there is a small, fairly static displacement after the pump pulse which is attributed to thermal expansion in some parts of the amplifier. These three sets are particularly informative since the pictures which are delayed until after the pump pulse is over still exhibit any distortion associated with stress induced birefringence and non-uniform pumping because the thermal relaxation time of the disc is of the order of 30 seconds*. On the other hand, the diffraction spots in these pictures are not blurred by the finite exposure time. The overall tentative conclusion drawn from these pictures is that the additional distortion arising from amplifier pumping is very small, (i.e., the beam divergence is increased by less than 10% beyond the diffraction limit). The corresponding increase caused by cold amplifier distortion appears to be ~20%. Of course these conclusions require confirmation by quantitative measurements.

* "Face Pumped Laser," General Electric Company, Semi-Annual Technical Summary Report, ONR Contract No. Nonr-4659(00), 1 December 1964-31 May 1965, p. II 51

a) 1050μsec



b) 1300μsec

Figure D9. Photographs Showing Effect oi "Exposure Time."

E. QUANTITATIVE DISTORTION ANALYSIS

The next set of experiments were designed to quantitatively measure the effects of distortion. First, mirror Q (see Figure D1) is removed so that the Fraunhofer diffraction pattern is projected by the microscope objective onto a variable diameter aperture in front of a photodiode (P_2). A beam splitter is placed at the entrance to the amplifier in order to monitor the input signal with the aid of photodiode P_1. The outputs signals received at P_1 and P_2 are separately integrated in time with the aid of an operational amplifier and oscilloscope so that we may easily compare the total energy received by each photodiode and adjust for variations in the output of the driver oscillator. By varying the aperture diameter (with the aperture remaining centered on the diffraction focus), one obtains the normalized integrated energy received as a function of aperture diameter. These data and the theoretical curve are plotted in the graph shown in Figure E1. We note that the experimental curve lies ~13% below the theoretical value for a 0.17" aperture diameter equal to the theoretical first minimum diameter which occurs at approximately the Airy disc diameter and results from the amplifier aperture truncating the Gaussian beam. At a diameter of 0.085" equal to $\sim\frac{1}{2}$ of the value for the theoretical first minimum, the experimental point lies at ~60% of the theoretical value of 0.7. These discrepancies may be due partially to a failure to center accurately the aperture on the diffraction focus. This centering error becomes more serious as the receiving aperture diameter decreases but for our experimental values of the diameter, this error is thought to be less than 10%. Most of the "discrepancy" is probably accounted for by the effect of the aberrations introduced by the cold amplifier and measuring optics. In fact the observed behavior agrees well with our expectations developed in the earlier theoretical discussion of wave front distortion effects.

It should be noted that the experimental and theoretical curves have similar slopes in the region of the theoretical diameter of the first minimum which is

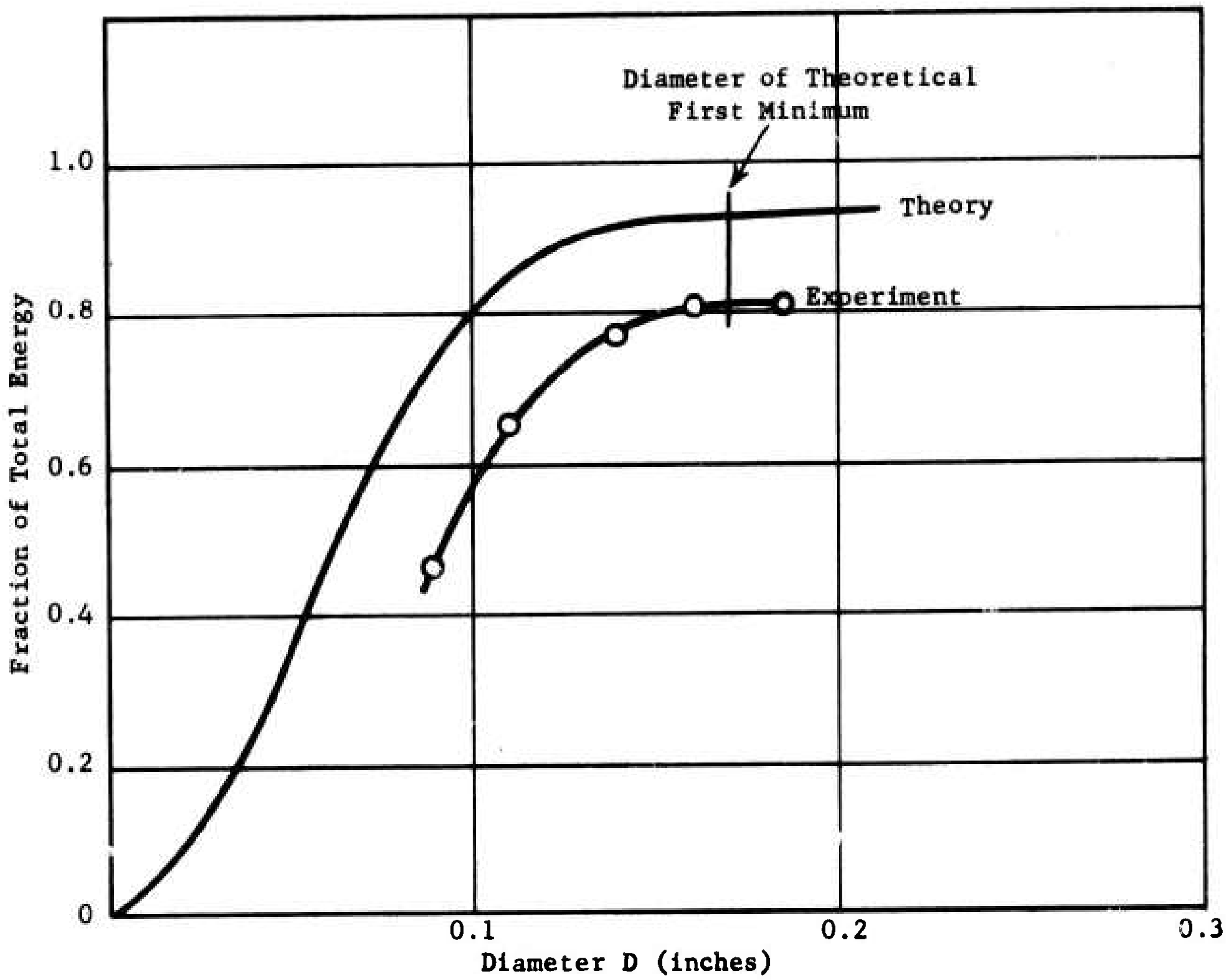


Figure E1. Fraction of Total Energy of Fraunhofer Diffraction Pattern Within Diameter D

consistent with the theoretical expectations that small aberrations only weakly perturb the position of minima and maxima, their primary effect being to reduce the central peak intensity and fill in the first minimum. The data in Figure E1 were normalized so that the experimental value of normalized integrated energy observed through a large aperture diameter (equal to several Airy disc diameters) is equal to the theoretical value. Additional experiments and theory both show this normalization to be justified. It should be added that the experimental data is compatible with the photographic data related to cold amplifier distortion.

The final measurement sought to determine the amount of distortion added by pumping the amplifier. This was measured at the time of maximum inversion (~650-720 μsec after the amplifier flash lamps are triggered). Since, from the photographic studies, the diffraction spot is known to be displaced vertically at this time, a vertical slit of width 0.110" (~0.65 times the diffraction width which locates the first theoretical minimum for the undistorted system) replaced the circular aperture in front of the photodiode (P_2). The driver oscillator was triggered with the amplifier cold and then at the time of maximum inversion when the amplifier was pumped (4,370 joules of capacitor energy delivered to each of the four laser modules). The energies received through the slit were each normalized to the respective input energies monitored by the other photodiode. When amplifier gain was divided out, it was found that the energy received through the slit was unchanged within the ~15% experimental uncertainty. This result is consistent with our theoretical expectations and photographic evidence.

F. MAXIMIZED INVERSION OF OPTIMUM CONFIGURATION

The maximum inversion obtainable with the active mirror configuration is estimated from recent experimental data using the detached mirror arrangement. Figure F1 shows the measured inversion efficiency (total stored energy at the time of maximum inversion divided by total lamp input energy) as a function of input energy. It should be noted that this data refers to the particular experimental arrangement described on the figure. The general shape of this curve can be accounted for reasonably well by considering only the effect of the spectral shift towards the ultraviolet of the flash lamp output as the input power is increased. For a rectangular pump pulse, the maximum inversion level is given by:

$$N = \frac{CEQ\tau}{T} \left(1 - e^{-T/\tau}\right) \qquad \text{(F-1)}$$

where

N = total stored energy (inversion)

C = efficiency of conversion from input power to absorbed power

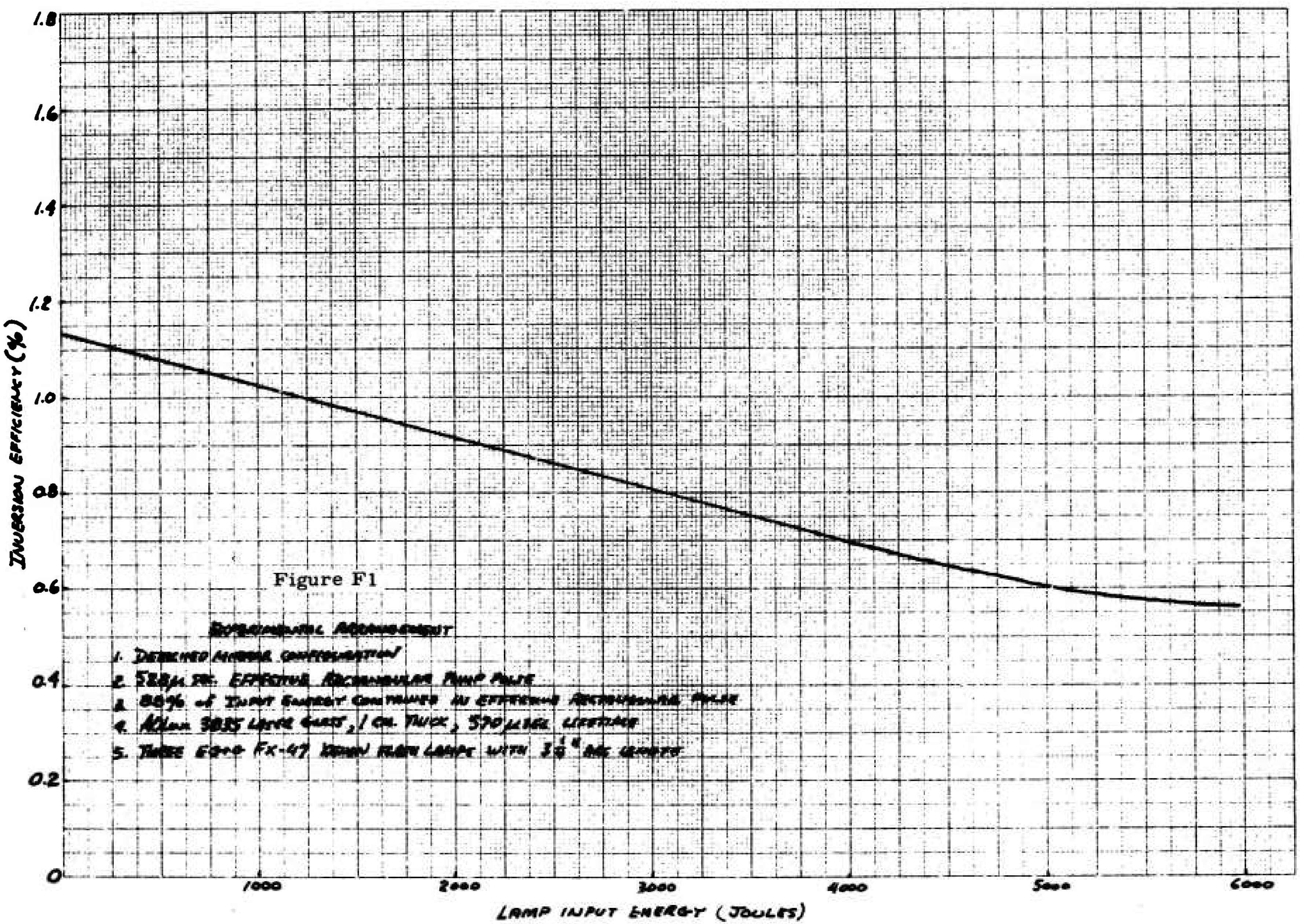
E = lamp input energy

Q = fraction of absorbed energy which goes into inversion

τ = fluorescent lifetime

T = duration of the effective rectangular pump pulse

For an optimized configuration it is proposed to operate three EG&G type FX 47 xenon flash lamps, each with an arc length of $3\frac{1}{4}$", at a total input energy of 6820 joules delivered in an approximately rectangular pump pulse of 1.17 milliseconds duration for pumping a 900 μsec lifetime Nd-doped glass. This choice of operating parameters is dictated by the fact that the maximum inversion compatible with the explosion limit of the flash lamps is achieved when the length of the rectangular pumping pulse is ~1.3 times the fluorescent lifetime of the laser glass. A relatively long lifetime is desired in order to reduce inversion losses through spontaneous emission. The proposed input lamp power



EXPERIMENTAL ARRANGEMENT
1. DETACHED MIRROR CONFIGURATION
2. 528 μ SEC. EFFECTIVE RECTANGULAR PUMP PULSE
3. 88% of INPUT ENERGY CONTAINED IN EFFECTIVE RECTANGULAR PULSE
4. 3835 LASER GLASS, 1 CM. THICK, 570 μSEC. LIFETIME
5. THREE EG&G FX-47 XENON FLASH LAMPS WITH 3 1/4" ARC LENGTH
INVERSION EFFICIENCY (%)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1000
2000
3000
4000
5000
6000
LAMP INPUT ENERGY (JOULES)

Figure F1

is 6820 joules/1.17 x 10^{-3} sec = 5.84 x 10^{6} watts. This value of input lamp power is the same as that obtained by utilizing 88% of 3500 joules delivered in 528 μsec; under the latter operating conditions the inversion efficiency is 0.75% as given in Figure F1. However this value of inversion efficiency must be corrected for changing the pulse length from 528 μsec to 1170 μsec, and fluorescent lifetime from 570 μsec to 900 μsec. That is, we have only accounted for an improvement in inversion efficiency resulting from an increase in C, the effect of a better spectral match between lamp output and pumping bands at lower lamp input power.

The effect of changing τ and T can be more readily visualized if Eq. (F-1) is rewritten in the following form to yield inversion efficiency:

$$\frac{N}{E} = \frac{CQ\tau}{T} \left(1 - e^{-T/\tau}\right) \tag{F-2}$$

Assuming that Q remains unaltered between the two Nd-doped glasses, the inversion efficiency is reduced by a factor of:

$$\frac{900}{570}\,\frac{528}{1170}\,\frac{1 - e^{-\frac{1170}{900}}}{1 - e^{-\frac{528}{570}}} = 0.86$$

However the net effect of the changes so far discussed is to yield an inversion efficiency of 0.86 x 0.75% = 0.645% at a lamp input of 6820 joules. This corresponds to a total stored inversion of 44 joules which compares with a maximum value of 29 joules in the present experiments using a detached mirror when the flash lamps are operated in each case at the same safety factor relative to the explosion limit. It is further proposed to increase the product of laser glass thickness times the Nd concentration from 5%-cm (the value for the data in Figure F1) to $12\frac{1}{2}$%-cm. As shown in Figure F2, this will increase the energy absorbed in the pump bands by a factor of 1.45.

There is experimental evidence that the reflector behind the flash lamps can be improved to increase the absorbed energy by 1.17.

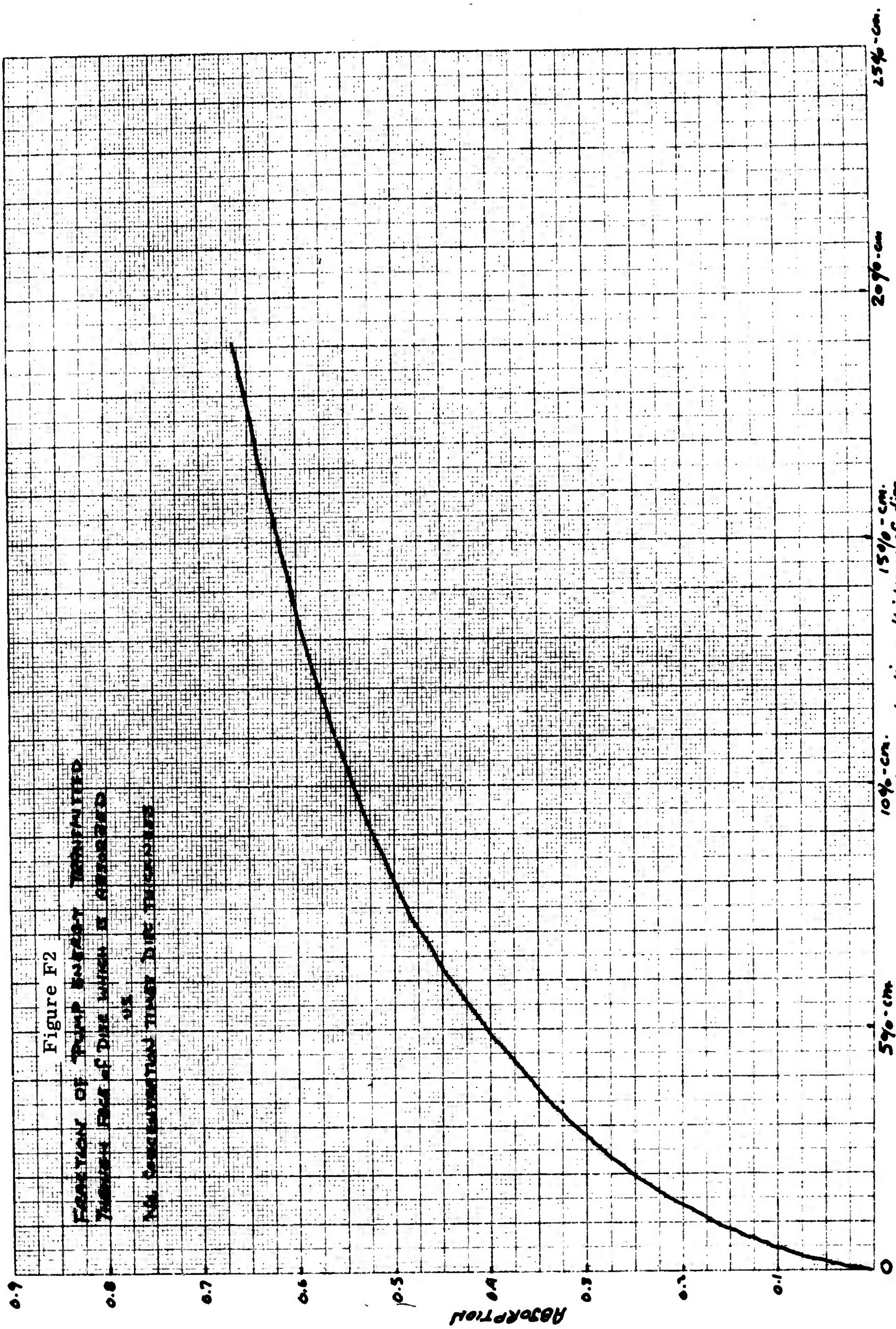

FRACTION OF PUMP ENERGY TRANSMITTED
THROUGH FACE OF DISC WHICH IS ABSORBED
vs
Nd CONCENTRATION TIMES DISC THICKNESS
ABSORPTION
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5%-cm
10%-cm.
15%-cm.
20%-cm
25%-cm.
Nd concentration x thickness of disc

Figure F2

By shaping the pump pulse to be approximately rectangular, all of the pumping energy is available to contribute to the maximum inversion as compared with 88% in the detached mirror experiments. Thus an improvement of 1.137 is possible.

A considerable loss of efficiency results from reflections at the following: 1) one flash-lamp water jacket-air interface, 2) two potassium chromate filter-air interfaces, 3) two separate mirror-air interfaces, and 4) one laser disc-air interface. By eliminating the detached mirror and using liquid immersion between the flash lamps and an active mirror, these reflections may be made negligible. An improvement in efficiency due to immersion by a factor of 1.67 is anticipated.

With all of the preceding improvements the inversion efficiency expected is then 0.645% x 1.45 x 1.17 x 1.14 x 1.67 = 2.1% for 6820 joules of lamp input energy. This means 142 joules of inversion distributed over 44.4 cm^2 of disc face area or 3.2 joules per cm^2 and 1.6 dB per round trip reflection from the active mirror.

Section III

PROGRAM SUMMARY

A. PURPOSE OF THE PROGRAM

Although laser designs have advanced considerably during the past few years, there has always been a need for lasers with higher power outputs and near-diffraction limited beams. In achieving the higher outputs self destruction of the laser material frequently occurred thereby establishing an upper limit in power or energy density at the radiating aperture. Thus it becomes clear that higher power and energy outputs require large radiating apertures.

If a conventional rod type laser configuration were to be scaled to provide a large aperture or diameter, it would be very difficult to obtain a high quality beam because of the optical pumping from the side or radial direction of the rod. This type of pumping produces thermal gradients in the rod as well as optical signal gain variations across the diameter. Furthermore a single long rod may suffer considerably from amplified spontaneous emission ("super-radiance") losses thereby limiting the output.

The purpose of the subject program has been to investigate some of the salient characteristics of a face pumped disc laser which offers the potential of a laser design with extremely high power or energy output in a near-diffraction limited beam. Each disc laser is optically pumped in a direction substantially normal to the disc face, and the laser beam is also essentially normal to the disc face. With the direction of the pump radiation, thermal gradients in the laser material, and laser beam direction essentially parallel to each other, the amount of beam distortion introduced across the laser aperture is minimal. This low beam distortion can be achieved independent of aperture diameter. Since the total power output is dependent on aperture diameter, the face pumped disc laser offers the potential of high power or energy output combined with low beam distortion. A high gain system will require several discs in series.

Large volumes of laser material with high optical quality can be obtained relatively easily from neodymium doped glass but with difficulty from crystalline material such as ruby. The subject program was carried out using neodymium doped glass discs. In the next section, a brief summary is presented of the theoretical and experimental investigation and the results of the present program.

B. SUMMARY OF INVESTIGATIONS AND RESULTS

The unique feature potentially offered by the disc laser is low beam distortion combined with high energy or power output. In the following summary, beam distortion is discussed first and then those features bearing on the output power and energy of the disc laser such as amplified spontaneous emission, and gain and stored inversion energy.

BEAM DISTORTION

One of the initial requirements for low distortion of the laser beam is high quality of the optical and laser components. At the outset of the program, it was difficult to procure neodymium doped laser glass of large sizes with high optical quality. However in due time it became relatively easy to procure discs with diameters of 3" or more, with negligible index variation. These discs are routinely finished optically to a flatness tolerance of 1/10 wavelength at 1.06 μ. With this tolerance it has been shown that the beam loss as determined by the optical energy contained within an Airy disc diameter ("main lobe" of radiation pattern) is less than 2% per disc, and an insignificant loss within twice the Airy disc diameter.

Another source of beam distortion is due to thermal effects on the laser disc attendant with optical pumping. Since the pump radiation is absorbed on one face of the disc, there will be a thermal gradient in the axial direction of the disc. This gradient will cause a flat disc to deform slightly with a surface having a long radius of curvature. Two disc laser designs were considered, the difference being in the position of the mirror relative to the disc. The mirror reflects 1.06 μ radiation and transmits the pump radiation incident from the flash lamps.

In one disc laser design, the mirror is separate but in close proximity to the laser disc which is low-reflection coated at 1.06 μ. In this design the thermally deformed disc will not degrade the beam significantly.

In the second disc laser design, the mirror is attached or deposited on one face of the laser disc. In this design the thermally deformed disc will behave as a weak spherical mirror. A typical value of the radius of curvature is very long, of the order of 10^3 meters. If during the signal pulse the amount of optical pumping is small, such as under Q-switched operation, then the effect of the thermally deformed disc may be compensated by a predetermined weak spherical lens.

The beam distortion studies have shown that the thermal effects in the total system can be made comparable to or smaller than the residual effects due to manufacturing tolerances of the optical components.

AMPLIFIED SPONTANEOUS EMISSION

A factor which may limit the maximum energy, power or gain achievable from a laser device is amplified spontaneous emission (ASE). In order to achieve high energy, power or gain from a laser device it is necessary to have a high density of population inversion. With laser material having large dimensions, very high inversion density is not possible because of ASE losses which increase exponentially with the dimensions.

The largest dimension of a disc is its diameter so that an upper limit exists for the diameter as dictated by ASE. Because of this limitation, a simplified theoretical and experimental investigation was carried out on two laser discs, viz., a) 6" diameter, 2% Nd doping, Eastman Kodak ND-11 silicate glass, 360 μsec fluorescent lifetime, and b) 3" diameter, 5% Nd doping, American Optical AOLux #3835 light barium crown glass, 570 μsec fluorescent lifetime. From fluorescent lifetime shortening measurements it is concluded that amplified spontaneous emission is not a serious problem for these two laser discs using the highest pumping level which was available provided the edge of each disc is made non-reflecting at 1.06 μ.

GAIN AND STORED INVERSION ENERGY

A high energy laser requires high stored population inversion energy. A common method of measuring inversion energy is indirectly through gain. The small signal gain of the disc laser was measured experimentally and the value was 85% of the theoretical value. For an active mirror configuration employing a 900 μsec fluorescent lifetime glass, a stored energy density of 3.2 joules/cm^2 appears attainable which will yield a small signal reflection gain of 1.6 dB per disc.

OTHER RESULTS

A face pumped disc laser offers an attractive design approach to a high power amplifier. However this approach is not very satisfactory in an oscillator configuration because of impractically tight tolerances required on the Fabry-Perot resonant cavity to achieve a mode diameter approaching the disc diameter.

RECOMMENDATIONS FOR FURTHER WORK

The foregoing program has demonstrated that the face pumped disc laser will be extremely useful as a high power amplifier with low beam distortion. Further work is required to establish the limits which are potentially achievable from an optimized design.

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13. ABSTRACT

This is the final report on investigations of the face pumped laser technique under this contract. Work performed during the last six months of the program is described. Also included are a review of the overall program objective and a summary of results obtained.